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DARK ENERGY AND DARK MATTER FROM COSMOLOGICAL OBSERVATIONS

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The present status of our knowledge about the dark matter and dark energy is reviewed. Bounds on the content of cold and hot dark matter from cosmological observations are discussed in some detail. I also review current bounds on the physical properties of dark energy, mainly its equation of state and effective speed of sound.

1 Introduction

The introduction of new observational techniques has in the past few years moved cosmology into the era of precision science. With the advent of precision measurements of the cosmic microwave background (CMB), large scale structure (LSS) of galaxies, and distant type Ia supernovae, a new paradigm of cosmology has been established. In this new standard model, the geometry is flat so that $\Omega_{\rm total} = 1$, and the total energy density is made up of matter ($\Omega_m \sim 0.3$) [comprised of baryons ($\Omega_b \sim 0.05$) and cold dark matter ($\Omega_{\rm CDM} \sim 0.25$)], and dark energy ($\Omega_X \sim 0.7$). With only a few free parameters this model provides an excellent fit to all current observations [1,2,4,7]. However, cosmology is currently very much a field driven by experiment, not theory. While all current data can be described by a relatively small number of fitting parameters the understanding of the underlying physics is still limited.

Here, I review the present knowledge about the observable cosmological parameters related to dark matter and dark energy, and relate them to the possible underlying particle physics models. I also discuss the new generation of experiments currently being planned and built, particularly those designed to measure weak gravitational lensing on large scales. These instruments are likely to bring answers to at least some of the fundamental questions about dark matter and dark energy.

2 Cosmological data

2.1 Large Scale Structure (LSS).

At present there are two large galaxy surveys of comparable size, the Sloan Digital Sky Survey (SDSS) [7,6] and the 2dFGRS (2 degree Field Galaxy Redshift Survey) [5]. Once the SDSS is completed in December 2005 it will be significantly larger and more accurate than the 2dFGRS, measuring in total about 10^6 galaxies.

Both surveys measure angular positions and distances of galaxies, producing a fully three dimensional map of the local Universe. From this map various statistical properties of the large scale matter distribution can be inferred.

The most commonly used is the power spectrum $P(k,\tau)$, defined as

$$P(k,\tau) = |\delta_k|^2(\tau), \qquad (1)$$

where k is the Fourier wave number and τ is conformal time. δ is the k'th Fourier mode of the density contrast, $\delta\rho/\rho$.

The power spectrum can be decomposed into a primordial part, $P_0(k)$, generated by some mechanism (presumably inflation) in the early universe, and a transfer function $T(k,\tau)$,

$$P(k,\tau) = P_0(k) T(k,\tau). \qquad (2)$$

The transfer function at a particular time is

found by solving the Boltzmann equation for $\delta(\tau)$ [128].

As long as fluctuations are Gaussian, the power spectrum contains all statistical information about the galaxy distribution. On fairly large scales $k \leq 0.1\,h/\mathrm{Mpc}$ this is the case, and for that reason the power spectrum is the form in which the observational data is normally presented.

2.2 *Cosmic Microwave Background.*

The CMB temperature fluctuations are conveniently described in terms of the spherical harmonics power spectrum $C_l^{TT} \equiv \langle |a_{lm}|^2 \rangle$, where $\frac{\Delta T}{T}(\theta,\phi) = \sum_{lm} a_{lm} Y_{lm}(\theta,\phi)$. Since Thomson scattering polarizes light, there are also power spectra coming from the polarization. The polarization can be divided into a curl-free ((E)) and a curl ((B)) component, much in the same way as $\vec{E}$ and $\vec{B}$ in electrodynamics can be derived from the gradient of a scalar field and the curl of a vector field respectively (see for instance [136] for a very detailed treatment). The polarization introduced a sequence of new power spectra, but because of different parity some of them are explicitly zero. Altogether there are four independent power spectra: C_l^{TT}, C_l^{EE}, C_l^{BB}, and the T-E cross-correlation C_l^{TE}.

The WMAP experiment has reported data only on C_l^{TT} and C_l^{TE} as described in Refs. [3,4]. Other experiments, while less precise in the measurement of the temperature anisotropy and not providing full-sky coverage, are much more sensitive to small scale anisotropies and to CMB polarization. Particularly the ground based CBI [58], DASI [59], and ACBAR [57] experiments, as well as the BOOMERANG balloon experiment [60,61,62] have provided useful data.

2.3 *Type Ia supernovae*

Observations of distant supernovae have been carried out on a large scale for about a decade. In 1998 two different projects almost simultaneously published measurements of about 50 distant type Ia supernovae, out to a redshift or about 0.8 [1,2]. These measurements were instrumental for the measurement of the late time expansion rate of the universe.

Since then a, new supernovae have continuously been added to the sample, with the Riess et al. [63] "gold" data set of 157 distant supernovae being the most recent. This includes several supernovae measured by the Hubble Space Telescope out to a redshift of 1.7.

3 Cosmological parameters

Based on the present cosmological data, many different groups have performed likelihood analyses based on various versions of the standard Friedmann-Robertson-Walker cosmology (see for instance [7,64] for recent analyses). A surprisingly good fit is provided by a simple, geometrically flat universe, in which 30% of the energy density is in the form of non-relativistic matter and 70% in the form of a new, unknown dark energy component with strongly negative pressure. Fig. 1 shows the allowed region from a combined fit of WMAP, SDSS, and Type-Ia supernova data.

In its most basic form, the dark energy is in the form of a cosmological constant where $w \equiv P/\rho = -1$. The only free parameters in this model are: Ω_m, the total matter density, Ω_b, the density in baryons, and H_0, the Hubble parameter. In addition to these there are parameters related to the spectrum of primordial fluctuations, presumably generated by inflation. Observations indicate that the fluctuations are Gaussian and with an almost scale invariant power spectrum. More generally, the primordial spectrum is usually parameterized by two parameters: A, the amplitude, and n_s the spectral tilt of the power spectrum. Finally, there is the parameter τ which is related to the redshift of reioniza-

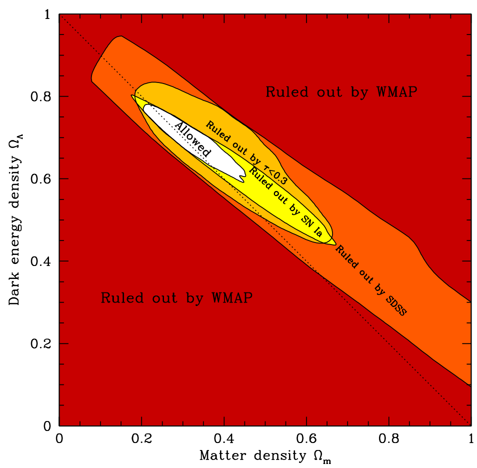

Figure 1. The 95% likelihood contour for Ω_m and Ω_Λ from WMAP, SDSS, and SNI-a data [with permission from [7]]

tion of the Universe. Altogether, standard cosmology is describable by only 6 parameters (5 if the spectrum is assumed to be scale invariant [a].

Adding other parameters to the fit does not significantly alter the determination of the 6 fundamental parameters, although in some cases the estimated error bars can increase substantially.

4 Dark matter

The current cosmological data provides a very precise bound on the physical dark matter density [7]

$$\Omega_m h^2 = 0.138 \pm 0.012, \qquad (3)$$

although this bound is somewhat model dependent. It also provides a very precise measurement of the cosmological density in baryons [7]

$$\Omega_b h^2 = 0.0230^{+0.0013}_{-0.0012}. \qquad (4)$$

[a]See [126,127] for a discussion about how to estimate the number of cosmological parameters needed to fit the data.

This value is entirely consistent with the estimate from Big Bang nucleosynthesis, based on measurements of deuterium in high redshift absorption systems, $\Omega_b h^2 = 0.020 \pm 0.002$ [120,121].

The remaining matter density consists of dark matter with the density [7]

$$\Omega_{\rm dm} h^2 = 0.115 \pm 0.012. \qquad (5)$$

The bound on the dark matter density in turn provides strong input on any particle physics model for dark matter. Space limitations allow only for a very brief review of the cosmological constraints on dark matter. Very detailed reviews can be found in [129,130].

4.1 WIMPs

The simplest model for cold dark matter consists of WIMPs - weakly interacting massive particles. Generic WIMPs were once in thermal equilibrium, but decoupled while strongly non-relativistic. For typical models with TeV scale SUSY breaking where neutralinos are the LSPs, one finds that $T_D/m \sim 0.05$. SUSY WIMPs are currently the favoured candidate for cold dark matter (see [130]). The reason is that for massive particles coupled to the standard model via a coupling which is suppressed by 1/TeV and with a mass of order 100 GeV to 1 TeV a present density of $\Omega_m h^2 \sim 0.1$ comes out fairly naturally. SUSY WIMPs furthermore have the merit of being detectable. One possibility is that they can be detected directly when they deposit energy in a detector by elastically scattering (see the contribution by Laura Baudis to these proceedings). Another is that WIMPs annihilate and produce high energy photons and neutrinos which can subsequently be detected (see the contribution by Rene Ong to these proceedings).

4.2 CDM Axions

WIMPs are by no means the only possibility for having cold dark matter. Another possi-

bility is that CDM is in the form of axions, in which case the mass needed to produce the correct energy density is of order 10^{-3} eV. In this case the axions would be produced coherently in a condensate, effectively acting as CDM even though their mass is very low (see for instance [65] for a recent overview).

4.3 Exotica

Another interesting possibility is that dark matter consists of very heavy particles. A particle species which was once in thermal equilibrium cannot possible be the dark matter if its mass is heavier than about 350 TeV [66]. The reason is that its annihilation cross section cannot satisfy the unitarity bound. Therefore, heavy dark matter would have to be produced out of thermal equilibrium, typically by non-perturbative processes at preheating towards the end of inflation (see for instance [67]). These models have the problem of being exceedingly hard to verify or rule out experimentally.

4.4 Hot dark matter

In fact the only dark matter particle which is known to exist from experiment is the neutrino. From measurements of tritium decay, standard model neutrinos are known to be light. The current upper bound on the effective electron neutrino mass is 2.3 eV at 95% C.L. [68] (see also the contribution by Christian Weinheimer to these proceedings). Such neutrinos decouple from thermal equilibrium in the early universe while still relativistic. Subsequently they free-stream until the epoch around recombination where they become non-relativistic and begin to cluster. The free-streaming effect erases all neutrino perturbations on scales smaller than the free-streaming scale. For this reason neutrinos and other similar, light particles are generically known as hot dark matter. Models where all dark matter is hot are ruled out completely by present observations, and in fact the current data is so precise that an upper bound of order 1 eV can be put on the sum of all light neutrino masses [69,70,71,72,73,74,75,76,77,78,79]. This is one of the first examples where cosmology provides a much stronger constraint on particle physics parameters than direct measurements. The robustness of the neutrino mass bound has been a topic many papers over the past two years. While some derived mass bounds, as low as 0.5 eV are almost certainly too optimistic to consider robust at present, it is very hard to relax the upper bound to much more than 1.5 eV [79]. The reason for the difference in estimated precision lies both in the assumptions about cosmological parameters, and in the data sets used.

In the future, a much more stringent constraint will be possible, especially using data from weak lensing (see section 6).

4.5 General thermal relics

The arguments pertaining to neutrinos can be carried over to any thermal relic which decoupled while relativistic. As long as the mass is in the eV regime or lower the free streaming scale is large than the smallest scales in the linear regime probed by LSS surveys. This has for instance been used for particles such as axions [80]. It should of course be noted that these axions are in a completely different different mass range than the axions which could make up the CDM. At such high masses, the axions would be in thermal equilibrium in the early universe until after the QCD phase transition at $T \sim 100$ MeV and therefore behave very similarly to neutrinos.

However, for relics which decouples very early, the mass can be in the keV regime. In that case it is possible to derive mass bounds using data from the Lyman-α forest which is at much higher redshifts and therefore still in the semi-linear regime, even at subgalactic scales. Using this data it has for instance been possible to set constraints on the mass

of a warm dark matter particle which makes up all the dark matter [81].

4.6 *Telling fermions from bosons*

There is a fundamental difference between hot dark matter of fermionic and of bosonic nature. First of all, the number and energy densities are different. For equal values of Ωh^2 this leads to different particle masses and therefore also different free-streaming behaviour. The differences are at the few percent level, and although not visible with present data, should be clearly visible in the future [131]. The difference between the matter power spectra of two different models, both with $\Omega_{\rm HDM} = 0.02$, can be seen in Fig. 2. Even more interesting, in the central parts of dark matter halos, the density of a bosonic hot dark matter component can be several times higher than than of a fermionic component with the same mass, purely because of quantum statistics [131]. The reason is that the distribution function, $f = 1/(e^{E/T}+1)$, for a non-degenerate fermion in thermal equilibrium has a maximum at $p = 0$ where $f = 1/2$. This bound also applies to the species after decoupling, and provides an upper bound on the physical density of such particles in dark matter halos. This is known as the Tremaine-Gunn bound [132,133,134,135]. Because there is no such limit for non-degenerate bosons, their density in dark matter halos can be many times higher than that of fermions. Unfortunately the effect is most pronounced in the central parts of dark matter halos where the density is dominated by cold dark matter and baryons, and therefore it might not be observable [131].

5 Dark energy

From the present supernova data alone, the universe is known to accelerate. In terms of the deceleration parameter q_0, the bound is

$$q_0 = -\frac{\ddot{a}a}{\dot{a}^2} < -0.3 \tag{6}$$

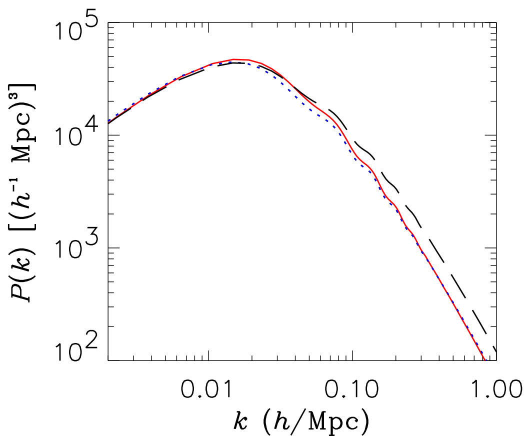

Figure 2. Linear power spectra for two different ΛHCDM models. The blue (dotted) line shows a model with three massless neutrinos and one massive Majorana fermion, contributing $\Omega = 0.02$. The red (solid) line shows the same, but with a massive scalar instead. The black (dashed) line is the standard ΛCDM model with no HDM. Note that these spectra have been normalised to have the same amplitude on large scales. [From [131]].

at 99% C.L. [63]. Such a behaviour can be explained by the presence of a component of the energy density with strongly negative pressure, which can be seen from the acceleration equation

$$\frac{\ddot{a}}{a} = -\frac{4\pi G \sum_i (\rho_i + 3P_i)}{3}. \tag{7}$$

The cosmological constant is the simplest (from an observational point of view) version of dark energy, with $w \equiv P/\rho = -1$. However, there are many other possible models which produce cosmic acceleration.

However, since the cosmological constant has a value completely different from theoretical expectations one is naturally led to consider other explanations for the dark energy.

5.1 *The equation of state*

If the dark energy is a fluid, perfect or non-perfect, it can be described by an equation of state w which in principle is constrain-

able from observations. Secondly, this dark energy fluid must have an effective speed of sound c_s which in some cases can be important.

A light scalar field rolling in a very flat potential would for instance have a strongly negative equation of state, and would in the limit of a completely flat potential lead to $w = -1$ [86,87,88]. Such models are generically known as quintessence models. The scalar field is usually assumed to be minimally coupled to matter, but very interesting effects can occur if this assumption is relaxed (see for instance [89]).

In general such models would also require fine tuning in order to achieve $\Omega_X \sim \Omega_m$, where Ω_X and Ω_m are the dark energy and matter densities at present. However, by coupling quintessence to matter and radiation it is possible to achieve a tracking behavior of the scalar field so that $\Omega_X \sim \Omega_m$ comes out naturally of the evolution equation for the scalar field [8,9,10,11,12,13,14,15,16].

Many other possibilities have been considered, like k-essence, which is essentially a scalar field with a non-standard kinetic term [17,18,19,20,21,22,23]. It is also possible, although not without problems, to construct models which have $w < -1$, the so-called phantom energy models [24,28,25,26,27,29,30,31,32,33,34,35,37,36,38,39].

From an observational perspective there are numerous studies in which the effective equation of state of the dark energy has been constrained.

The simplest parametrization is $w =$ constant, for which constraints based on observational data have been calculated many times [82,83,84,85]. The bound on the equation of state, w, assuming that it is constant is roughly (see [41,90,40,64])

$$-1.2 \leq w \leq -0.8 \tag{8}$$

at 95% C.L. Very interestingly, however, there is a very strong degeneracy between measurements of w and the neutrino mass $\sum m_\nu$. When the neutrino mass is included in fits of w the lower bound becomes much weaker and the allowed range is

$$-2.0 \leq w \leq -0.8 \tag{9}$$

at 95% C.L. [79]. The result of a likelihood analysis taking both parameters to be free can be seen in Fig. 3.

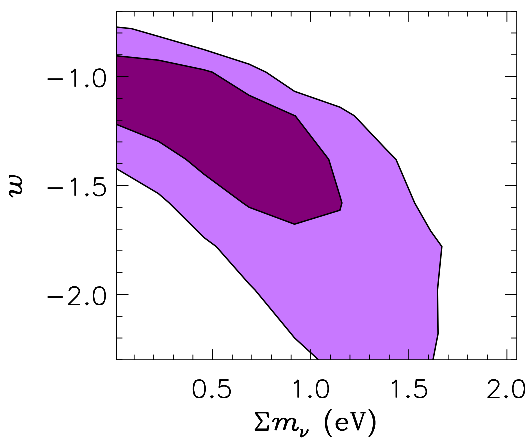

Figure 3. The 68% (dark) and 95% (light) likelihood contours for m_ν and w for WMAP, SDSS, and SNI-a data. [From [79]]

Even though a constant equation of state is the simplest possibility, as the precision of observational data is increasing is it becoming feasible to search for time variation in w.

At present there is no indication that w is varying. Even though the present Type Ia supernova data seem to favour a rapid evolution of w, this indication vanishes if all available cosmological data is analysed [41,90,40,64] (for other discussions of a time-varying w, see for instance [42,43,44,45,46,47,48,49,50,51,52,53,54,55,56,91,92,93,94,?,96].

5.2 *The sound speed of dark energy*

In general the dark energy speed of sound is given by

$$c_s^2 = \frac{\delta P}{\delta \rho}, \tag{10}$$

if it can be described as a fluid. The perturbation equations depend on the speed of sound in all components, including dark energy, and therefore c_s^2 can in principle be measured [122,123,124,125].

For a generic component with constant w, the density scales as $a^{-3(1+w)}$, where a is the scale factor. Therefore, the ratio of the energy density to that in CDM is given by $\rho/\rho_{\rm CDM} \propto a^{-3w}$. If w is close to zero this means that dark energy can be important at early times and affect linear structure formation. If, on the other hand, w is very negative, dark energy will be unimportant during structure formation. This also means that since $w \leq -0.8$ there is effectively no present constraint on the dark energy equation of state. In Fig. 4 we show current constraints in w and c_s^2.

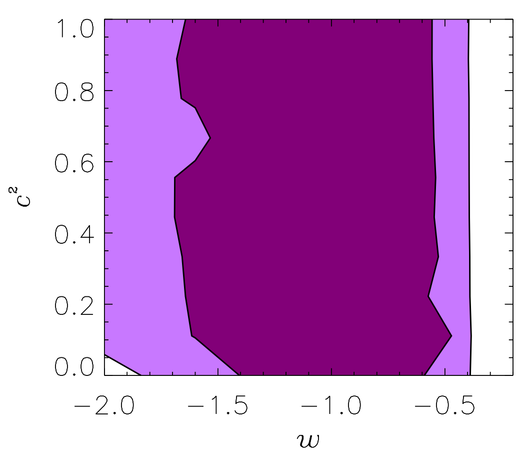

Figure 4. The 68% (dark) and 95% (light) likelihood contours for w and c_s^2 for WMAP, SDSS, and SNI-a data. [From [125]].

5.3 Dark energy or modified gravity?

A potentially very interesting possibility is that what we perceive as dark energy is in fact a modification of gravity on very large scales. General relativity has been tested to work in the weak field regime up to supergalactic scales. However, it is possible that at scales close to the Hubble horizon there might be modifications.

One possible scenario is that there are extra spatial dimensions into which gravity can propagate. For instance in the Dvali-Gabadadze-Porrati model [97], the standard model is confined to a 3+1 dimensional brane in a 4+1 dimensional bulk where gravity can propagate. On small scales, gravity can be made to look effectively four dimensional by an appropriate tuning of the model parameters, whereas on large scales gravity becomes weaker. This leads to an effect very similar to that of dark energy. Based on this idea, other authors have taken a more observational approach, adding extra terms to the Friedmann equation [98,99,101].

In this case the dark energy has no meaningful speed of sound since it is a change in gravity. However, exactly since it affects gravity it also affects the way in which structure grows in the universe. In [100] it was found that, unless the cross-over scale has very specific and fine tuned values, models with modified large scale gravity are almost impossible to reconcile with present observations.

6 Future observations

6.1 Cosmic microwave background

In the coming years, the present CMB experiments will be superseded by the Planck Surveyor satellite [102], due to be launched in 2007. It will carry instrumentation similar to that on the latest BOOMERANG flight, but will carry out observations from space, and for several years. The expectation is that the project will measure the CMB spectrum precisely up to $l \sim 2500$, being essentially limited only by foreground in this range. This experiment will be particularly important for the study of inflation because it will be able to measure the primordial spectrum of fluctuations extremely precisely.

On a longer timescale there will be dedicated experiments measuring small scales,

such as the Atacama Cosmology Telescope [103]. Small scale observations will be instrumental in understanding non-linear effects on the CMB, arising from sources such as the Sunyaev-Zeldovich effect and weak gravitational lensing.

6.2 Type Ia supernovae

There are several ongoing programs dedicated to measuring high redshift supernovae. For instance the Supernova Legacy Survey is currently being carried out at the CFHT [104]. ESSENCE [105] is another project dedicated to improving the current measurement of w. The future Dark Energy Survey [106] is expected to find about 2000 Type Ia supernovae, and the Supernova Acceleration Probe (SNAP) satellite mission (one of the contenders for the NASA Dark Energy Probe program) will find several thousand supernovae out to redshifts of order 2 [107].

6.3 Weak lensing

Perhaps the most interesting future probe of cosmology is weak gravitational lensing on large scales. The shape of distant galaxies will be distorted by the matter distribution along the line of sight, and this effect allows for a direct probe of the large scale distribution of the gravitational potential (see for instance [108] for a review). Just as for the CMB the data can be converted into an angular power spectrum, in this case of the lensing convergence [108,109,110,111]. Several upcoming surveys aim at measuring this spectrum on a large scale. The first to become operational is the Pan-STARRS [112] project which will have first light in 2006. In the more distant future, the Large Synoptic Survey Telescope [113] will provide an even more detailed measurement of lensing distortions across large fractions of the sky.

6.4 The impact on cosmological parameters

Many of the cosmological parameters will be measured much more precisely with future data. For the standard cosmological parameters, a detailed discussion and analysis can be found in [114]. As an example, the bound on the physical matter density could be improved from the present ± 0.012 to ± 0.0022, at least an improvement by a factor 5.

With regards to hot dark matter, the neutrino mass could be constrainable to a precision of $\sigma(\sum m_\nu) \sim 0.1$ eV or better [115,116,117,118,119,79], perhaps allowing for a positive detection of a non-zero mass.

The equation of state of the dark energy could be measurable to a precision of about 5%, depending on whether it varies with time [40].

7 Discussion

We are currently in the middle of an immensely exciting period for cosmology. We now have estimates of most basic cosmological parameters at the percent level, something which was almost unthinkable a decade ago. Cosmology is now at the stage where it can contribute significant new information of relevance to particle physics. One notable example is the density of cold dark matter, which is relevant for SUSY parameter space exploration. Another is the bound on the mass of light neutrinos which is presently significantly stronger than the corresponding laboratory bound.

The precision with which most of the cosmological parameters can be measured is set to increase by a factor of 5-10 over the next ten years, given a whole range of new experiments. For the foreseeable future, cosmology will be an extremely interesting field, and its relevance to particle physics is set to increase with time.

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